EFFECTIVENESS OF STANDARDS FOR MITIGATING DAMAGE IN CONCRETE DUE TO MATERIALS DEFICIENCIES

By:
Toy Poole and Timothy Martin
CTLGroup
3737 Executive Center Drive
Austin, TX 78731
Phone: (512) 219-4075
tpoole@ctlgroup.com
tmartin@ctlgroup.com

PRESENTED FOR THE
2014 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Galloway, New Jersey, USA

August 2014

INTRODUCTION

Standards are an important part of the process of technology transfer from R&D to practice. The purpose of this report is to explore the effectiveness of standards in accomplishing this task for materials properties that cause damage to concrete. The main thesis is that standards do a good job of addressing the main technical issues relating to materials properties, but seemingly less critical issues are sometimes overlooked. This condition sometimes persists for a long time, and sometimes is found to be the basis of chronic problems in practice that can be significant.

Modern hydraulic-cement concrete construction in the US dates to the mid nineteenth century. Standards development for concrete and concrete making materials became a significant process starting around the start of the twentieth century. ASTM (formerly American Society of Testing and Materials), which is the principal standards development organization in the US for cement and concrete materials was organized at about this time. ASTM committee C1 on cement was organized in 1902 and committee C9 on concrete and concrete materials was organized in 1914. The American Association of State Highway Transportation Officials (AASHTO) also develops and manages concrete and concrete materials standards. Many AASHTO standards are based on ASTM standards and some are uniquely AASHTO developed. ACI (formerly American Concrete Institute) is the principal organization that develops and maintains standards on concrete design and construction practice.

During these early years there were significant problems with concrete materials that resulted in production of inferior concrete. Considerable effort was put into research on the fundamental causes of these problems and much progress was made. Many of the standards still in use have their origins in this early period. While all standards are updated on a regular basis, as required by regulations of the managing standards organization, a number of them have gaps in coverage of problems that seem to have persisted for a long time and are the source of chronic problems. The problems caused by these gaps tend be sporadic in nature, but when they do occur, the consequences to the particular structure can be significant with respect costs and/or service life. Idorn [1] has written an excellent documentation of this history.

Some of the problems are general in nature, found commonly in many standards. These include significance of field service records, precision and bias of test methods, sampling, and basis for specification limits. Other problems are specific to details of individual standards. Some examples of these will be presented.

GENERAL PROBLEMS IN MATERIALS STANDARDS

Origin of Specification Limits

Determining meaningful acceptance limits for a specification on a property of a material can be a difficult and uncertain process. A limit that is too restrictive can result in material being unnecessarily rejected, particularly if the test method precision is poor. If the limit is insufficiently restrictive, then poor material is likely to be accepted.

Most of the specification limits on concrete materials were determined many years ago. Too often there is little or no record of the logic behind the limit, so it can be difficult to review the competence of a specification limit.

The basis of specification limits is varied. Some possibilities include:

- Field service records;
- Comparative testing in the laboratory;
- Professional judgment; and
- Taken from a specification on a similar material.

Regardless of the origin, if the specification is very old, it is likely that the origin in unknown.

Lack of information on the origin of a specification limit can result in a rather fossilized specification that may not be suitable for current use. It is of course possible to initiate an investigation anew, but this is often expensive and possibly controversial to users with whom the current limits are deeply embedded.

An example is ASTM C618[1], the specification for coal fly ash for use in concrete. Class F and Class C ashes are discriminated based on the sum of the silicon, aluminum and iron oxides at 70%. At the extremes Class F ashes may contain over 90% of these oxides, while at the other extreme, Class C ashes may contain no more than 50%. Ashes tend to vary in performance properties over this range, but there is no perceptible discontinuity that recommends 70% as a likely limit. The basis for the 70% number may be known, but attempts to find it have so far failed.

Field Service Records

There is a strong long-standing belief in the primacy of field service records as the ultimate validation of materials test methods and specifications. The value of field service records is a well-founded concept; however practical problems in assembling legitimate field service records prevents the potential value from being realized in many cases and this often goes unrecognized.

There are at least three common problems with the field-service records. One is that field service must be based on existing structures sufficiently old that any materials related problem would be expected to have developed if the potential exists. The expected service life of the structure should play into the determination of a minimum age considered acceptable. For example, in some cases an adequate service record for alkali-aggregate reactions is sometimes considered to be 10 years. AAR often takes considerably longer than 10 years to be identified in a structure.

---

[1] ASTM C618. Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

The second problem is that the structures used to document the field service record must be constructed with the same materials, or materials that are fundamentally the same, in similar proportions, and exposed to similar environmental conditions as anticipated for new construction. There was a period in concrete construction when this might have been plausible. However materials used in concrete in modern construction can vary significantly over time due to changes in manufacturing resulting from regulatory requirements and competitive pressure from other producers. As a result it is probably more difficult to construct meaningful field service records than in the past.

The third problem is that long-term preservation of construction records is rare. Construction records are commonly lost within a few years of construction. Even many major governmental agencies have a poor history of construction records management on the critical items after a few years. Consequently when materials-related failures do occur, it is difficult to reconstruct the properties of the materials used in the original construction.

Precision

Precision of materials test methods is an often neglected but very important detail affecting the process of screening materials for acceptability for concrete construction. For many years most test methods contained no information on precision.

As a result of a revision in ASTM regulations in the 1980's, almost all ASTM concrete materials test methods now contain precision statements. The information in a precision statement gives the user of the test method information on how much the determined value of a material property can be obscured by the random error of the test method. This helps the user of the test method to separate real variation in a material property from apparent variation attributable to testing variation. It also helps the user determine the likelihood of making a mistake in acceptance of a material due to random testing error.

Precision statements usually have two parts. One deals with test method variation among tests in a single laboratory. This is usually termed single operator or within-laboratory variation. The other part deals with variation that occurs among two or more laboratories testing the same material. This is usually termed between-laboratory or multi-laboratory variation.

The within-laboratory precision is mostly used for the purpose of monitoring internal laboratory operations. The multi-laboratory precision is the statistic most meaningful in acceptance testing because it addresses the difference between a materials supplier's test results and a materials user's test results.

If the between-laboratory precision is poor, it becomes very difficult to determine with much certainty from the acceptance test data the true value of the property being measured. This variation can also be the source of significant purchasing disputes and errors in acceptance that can be damaging to either the supplier, if a good material is rejected, or to the user, if an unsatisfactory material is accepted.

During the process of filling the missing precision statements, little attention was paid to the significance of the level of precision that was reported. This is starting to change. Although there has been no systematic review of precision of test methods, there does seem to be a chronic problem with test methods and poor precision.

An example is ASTM C1293[2]. This test method is used to evaluate the tendency of an aggregate to cause damaging alkali-aggregate reaction in concrete. It is a length-change test method. The typical specification limit for this has been set at ≤0.04% after one year exposure to the test condition. The between laboratory coefficient of variation (CV) for this method has been determined to be 23%. The standard deviation at 0.04% expansion is then 0.01%.

Two laboratories can be expected to differ in test results on the same aggregate by as much as 2.8 times the standard deviation, or 0.03%. Thus it isn't improbable that one laboratory might obtain a test result of 0.03% while another might get 0.06%. One test result indicates an innocuous aggregate, while the other indicates a reactive aggregate. This difference would end up being the object of a dispute – which is not a good outcome after one year of testing!

It is generally desirable for the coefficient of variation of a test method to be such that laboratory differences are in the rounding of the last digit of the specification limit. A CV of about 5% is usually sufficient to achieve this objective. Many test methods have a CV considerably larger than 5%.

Generally, poor precision is a result of equipment differences, different laboratory conditions, or differences in the way different operators interpret the details of the test procedure. It can be difficult to identify and repair these effects.

Sampling

It is rather a common materials acceptance procedure to take a single or limited-scope sample of a material from a source and then to assume it is representative of the entire source. For very uniform materials, this practice may not cause any problems. For example cement manufacture is a highly controlled process in modern cement plants, so less extensive sampling is often suitable. However, for materials that have high potential for within-source variability, such as some aggregate sources and some fly ash sources, this can lead to a lot of surprises.

As an example of such a problem occurred with a Corps of Engineers dam built in the southeast in 1970-71, as reported in Poole [2]. The aggregate source was a nearby sedimentary rock quarry that had been approved. Pre-construction testing indicated that the rock was not susceptible to alkali-aggregate reaction. Part of the way through the construction it was noticed that the coarse aggregate stockpile looked a little different than usual and test samples were submitted for analysis. By the time the results were obtained about 6 weeks of construction had occurred. Test results indicated that the quarry operation had apparently gotten into some material susceptible to AAR. The quarry operation shifted to another location and the structure was completed.

Twenty-five years later it was suspected that there was some AAR damage in the structure. An investigation revealed that the damage was localized to two to three lifts in each monolith.

---

[2] ASTM C1293. Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction

Further investigation revealed that the lifts that contained the damage were placed during the period in 1970 when this questionable material had appeared in the stockpile. The AAR is causing mechanical alignment problems in spillway gates, but the structure is still operational with periodic maintenance.

It was concluded that there was a location in the quarry of poor material that had not been revealed by the pre-construction sampling.

MATERIALS RELATED DAMAGE EXAMPLES

D-Cracking

D-cracking is a materials related damage caused by concrete aggregate that expands and cracks when exposed to cycles of freezing and thawing when saturated with water. It is commonly associated with concrete pavements, but can occur in any type of structure in which the requisite conditions develop. Pavements are eventually destroyed by D-cracking, but it may take many years to reach that point.

The problem occurs in aggregates that easily stay saturated with water. For an aggregate to be susceptible it must be relatively porous so that a large amount of water is trapped within the rock, but the porosity structure must be fine enough that it does not quickly drain to a less than saturated state. This represents a fairly narrow range of rocks, but can be locally common.

There are two ASTM methods used to evaluate aggregate for D-cracking potential: C88[3] and C666[4] used in combination with C1646[5]. Neither of these methods is entirely suitable for this purpose.

Method C88 is an old method (first published in 1931) in which the aggregate is exposed to cycles of wetting and drying in a magnesium or sodium sulfate solution. The principle behind the test is that these salts form crystals in the voids of the aggregate particle, which then swell and shrink as a result of the wetting and drying cycles. This crystal phenomenon was believed to simulate the swelling and shrinking of water in a confined space that occurs during freezing and thawing cycles. The test is relatively simple to run and results are made available in a few days.

The coefficient of variation for this test when using magnesium sulfate, which is the salt specified in concrete aggregate specification C33 (first published in 1921), is 25%, which is not good precision. The test is also apparently quite aggressive and sometimes reported to over represent a true freezing and thawing condition. It is stated in the test method that it should not be used for acceptance testing because of the poor precision. However is continues to be cited as the referee test in C33[6].

---

[3] ASTM C88. Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate

[4] ASTM C666. Test Method for Resistance of Concrete to Rapid Freezing and Thawing

[5] ASTM C1646. Practice for Making and Curing Test Specimens for Evaluating Resistance of Coarse Aggregate to Freezing and Thawing in Air-Entrained Concrete

[6] ASTM C33. Specification for Concrete Aggregates

The consequence of relying on this test for acceptance is that a good aggregate could easily be rejected as being unsuitable. This is of economic importance to the cost of construction.

C666 (first published in 1967) is the only test method that is suitable for testing a full concrete specimen for resistance to cycles of freezing and thawing. As written, this method does not contain sufficient detail on how to modify the test to make it specific to D cracking. **C1646** (first published in 2007) contains this information.

This combination of test procedures in design, appears to be a good simulation of a natural exposure pertinent to the D-cracking problem and is the referee test procedure by many state and federal agencies. The method is accelerated in the sense that the cycles of freezing and thawing occur much more rapidly than is normal in nature. The test requires 60 days or more to run, depending on the user's choice of pre-exposure curing and choice of the time period of the freezing and thawing cycles. It is also more expensive than C88 due to the more complicated specimen preparation and equipment requirements.

Although C1646/C666 appears to be a more technically realistic test method, careful inspection of the precision statement in C666 reveals some possible problems in that there is no information on between-laboratory precision. As discussed above, between-laboratory precision is an important property of a test method. The absence of this information makes the use of the test method for acceptance testing questionable.

Pertinent to this problem is a study reported in COE [3] executed by the Corps of Engineers about 60 years ago using a test method that was a precursor to the current procedure. This included 7 laboratories each supplied with identical materials for fabricating and testing for aggregate durability. The resulting durability factors ranged from over 90% to less than 40%. The average durability factor was 64%, with a standard deviation of 19% and a CV of 29%. This cannot be taken as a definitive study, but it is an indicator that there may be a problem with variation in equipment and execution of procedures used in different laboratories.

Practical experience with Corps of Engineers testing in recent years has shown a rather common occurrence of disagreements with contractor's test data from private laboratories used by contractors for acceptance purposes. The Corps' data tended to show durability deficiencies while the private lab showed compliance. This disagreement has resulted in significant cost factors for the contractors to locate and import other aggregate sources that would meet the requirement according to the Corps' laboratory.

In a recent development, one state DOT laboratory has determined that the 300 cycle basis for the test, as written in C666, is insufficient to reveal deleterious aggregate and is investigating a 600 cycle basis which is believed to better simulate the number of freezing and thawing cycles in that state over the course of the expected service life of highway pavements (20 yr). The rationale for this modification is based on field service records. Suppliers are disputing the field service records, and further arguing that this modification is a deviation of a well-established feature of the test method. The basis for the 300 cycle is unknown at present, so resolving this issue is difficult.

Further complicating the issue is that many aggregates that have this potential are sedimentary rocks. Sedimentary rock quarries quite often are heterogeneous with respect to rock types. So a given quarry might have zones of acceptable rock and zones of unacceptable rock that must be identified and segregated. Although state agencies are probably in a position to do a complete quarry investigation to discover any such details, probably most concrete construction is done on the basis of a single sample of current production for the quarry.

Air Entraining

Before 1940, or so, the fact that concrete in wet and cold locations slowly deteriorated due to cycles of freezing and thawing was considered an unavoidable reality. The mechanism by which freezing of water in a confined space causes damage is well established. It is based on the unusual property of water of become less dense (expanding) as falling temperatures closely approach the freezing point. If it is trapped in a space, then this expansion is sufficient to fracture concrete. That a solution was not found for concrete for many years was because no one knew how to solve the problem.

It was discovered in the 1940's that forming a pattern of small air bubbles in the cement paste fraction of concrete will provide a mechanism for accommodating the expansion of freezing water just before freezing. The effectiveness of this technique depends critically on the size and spacing of these air bubbles, which can be tricky to deliberately engineer. The standard terminology for these two air void parameters are surface area and spacing factor, respectively.

The problem in construction has always been in knowing that the necessary air void parameters of in-place concrete have been successfully developed. Currently there is no test method for doing this until after the concrete has hardened sufficiently for samples to be extracted, prepared, and tested according to C457. This is not usually done because of the impracticality and potential disruption of delaying acceptance of concrete until after a structure or part of a structure is built.

It turns out that the total air content of fresh concrete, which is practical to measure prior to placement, usually correlates reasonably well with the important air void parameters in hardened concrete. Therefore the basis of project specifications is always the total air content of the fresh concrete prior to consolidation (ACI 318[7]). It is not usual practice to do the analysis on hardened concrete unless there is reason to believe the standard acceptance process was flawed.

Unfortunately the relationship between total air in fresh concrete and air void parameters in concrete sometimes does not hold. Several factors can come into play. One is that part of the entrained air can be lost during consolidation. Another is that sometimes a few very large bubbles form instead of the many small bubbles intended. Another is that sometimes the entrained air will cluster near the edge of aggregate particles, leaving much of the cement paste devoid of effective air voids. This represents an unfortunate case of the required total air being in the concrete, but it not functioning to protect the concrete because the air void parameters are not at the required levels.

---

[7] ACI 318-08. Building Code Requirements for Structural Concrete. ACI International, Farmington Hills, MI.

This problem is one for the owners of the structures to solve. Unless the contractor has responsibility for long-term maintenance as part of the contract, the properties of the air in hardened concrete is not much of a problem for them since their only responsibility is to insure that the correct total air content is in the fresh concrete when delivered to the placement. It is in the interest of the owner that a procedure be developed that can be used as the basis of an acceptance requirement that captures any disconnect between total air and desired air void parameters.

One approach currently being used by some is to require higher levels of total air than required by current guidance with the hope that at least enough will remain with the necessary dispersion after consolidation. This practice would tend to have significant negative effects on strength, so other adjustments to the concrete mix are required to compensate for this.

Another approach is to require a test placement of concrete prior to the start of construction that could be cored and air void parameters determined to insure that total air was an accurate assessment of in-place air.

Such test strips are required in some airfield paving, but air void analysis of hardened concrete has not typically been part of the evaluation procedure, apparently due to the common problem of schedule pressure.

Methods for determining air void parameters in fresh concrete after consolidation are currently appearing in research efforts and standardization has been initiated and reported in a presentation by Tabb [4]. Perhaps this approach can help resolve this problem.

Alkali Aggregate Reaction

Alkali aggregate reaction (AAR) is another material related distress that emerged as an important item during the major public works programs in the 1930's. Research in the 1940's identified the major factors involved: high pH in the cement pore fluid, which were traceable largely to cement alkalis (sodium and potassium), and metastable components of some aggregates (Idorn 1997). The result of the reaction is an expansive gel competent to cause internal stresses in concrete to dimensional changes in the structure and cracking.

Two forms of AAR are recognized. Alkali-silica reaction (ASR), which usually involves silicate rocks, but sometimes occurs in carbonate rocks with siliceous inclusions. Alkali-carbonate reaction (ACR) involves certain forms of dolomite rocks. ASR is much more prevalent than ACR and is the subject of much more attention from research and standards development.

Unlike most of the other materials related damage problems, AAR has had a longer period of R&D and standards development than average. The problem was thought solved for many years, but then examples from older structures showed this not to be totally true, as reported for military airfield pavements by Rollings [5]. A new research and standards-development effort was initiated and continues through the present time. As a result of this evolution the catalog of standards is a bit longer for this one than average and there is currently a lot of recent activity in standards organizations on important details (Table 1).

Table 1. Listing of test methods and guides for AAR testing.

Test Method (1st published)	Test Duration	Between-Lab CV	Use	Comments
ASTM C227 (1950)	6 – 12 m	ND[a]	aggregate screening – ASR	mortar test, now little used
ASTM C289 (1952)	2 d	ND[a]	aggregate screening – ASR	Chemical test, no little used
ASTM C441 (1959)	16 d	45%[b]	mitigation – ASR	Modification to C227, used in cement spec C595, C1157
ASTM C1105 (1989)	3 – 12 m	23%	aggregate screening - ACR	Not specific to ACR
ASTM C1260 (1989)	16d	15%	aggregate screening – ASR	much used
ASTM C1293 (1995)	1 – 2 y	23%	aggregate screening & mitigation – ASR	Considered the referee TM
ASTM C1567 (2004)	16d	15%	mitigation - ASR	much used
AASHTO PP 65 (2010)			general guide to aggregate screening and mitigation	Integrates all TM's & specs

[a]No between-lab precision determined
[b]No between-lab precision determined, estimated from other data

Recent research on mitigation of AAR sponsored by FHWA has resulted in a practice that uses the newer length-change test methods (C1260[8], C1293, and C1567[9]) and mitigation concepts. These are captured in AASHTO PP 65[10] (first published in 2010) based on a report by Thomas, Fournier, and Folliard [6].

C1260 and C1567 are both short term, highly aggressive tests. These tests are collectively referred to as accelerated mortar bar tests (AMBT). These tests have long had the reputation for being overly aggressive, thus failing many materials that are believed to be acceptable. This is sometimes called a false positive. The AASHTO practice does not recommend rejecting materials based solely on these tests. It has now become apparent the AMBT's also sometimes give false negatives, which cause faulty material to be accepted.

C1293 is a concrete test which is much less accelerated than the mortar tests (38 C). It is the only test suitable for evaluating job concrete mixtures and is considered to be the definitive test method. A major drawback is the long test period, which inhibits its practical use. The test period is 1 year for aggregate screening and 2 years for evaluation of mitigation. This is the test method which is considered to be the definitive test.

---

[8] ASTM C1260. Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)

[9] ASTM C1567. Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)

[10] AASHTO PP65. Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction

A notable item common to all of these standards is either the absence of precision information or the relatively poor between-laboratory precision, as shown in Table 1. This probably contributes significantly to the false negatives and false positives that occur.

In spite of the above described problems, the procedures have accomplished a significant improvement in the status of acceptance testing of materials pertinent to AAR than existed 15 - 20 years ago. Because of insufficient field service records, the development of field exposure test sites has been initiated in several locations. These have been very useful for verification of test methods and mitigation practices. Field exposure studies have verified most of the procedures to be sound for service life up to about 20 – 25 years in colder climates, but maybe somewhat less in warmer climates as reported by Fournier et al. [7]. But there is still doubt about the effectiveness for very long service life.

A practice developed in Department of Defense construction of airfields is to restrict the acceptance limits on materials to levels more conservative than is generally used in PP 65. Based on field exposure data, this approach appears to be competent to reduce the incidence of false negatives to a low level, however as expected, this practice also results in more materials being rejected than before. In general the practice has received a good deal of criticism for not following the standard protocol.

Coal Fly Ash

Coal fly ash was first used in concrete construction in the US in the 1930's for purposes of helping to mitigate thermal stress in large dams. It was later found to be also good for mitigating certain materials related issues, such as alkali-silica reaction and sulfate attack. In the 1970's the federal government, in response to the Resource Recovery Act, required that all federal construction use fly ash as a partial replacement for portland cement, unless not recommended for technical reasons. Today coal fly ash is considered to be an important component in most concrete construction.

The first ASTM standard for coal fly ash, C350[11] was first published c1955. This was later combined with a specification for natural pozzolan and the designation changed to C618 in 1968. Two classes of fly ash are defined based on the major chemical components. Silicon-aluminum glass is the principal reactive component of Class F fly ashes. Various calcium compounds are the principal reactive components of Class C fly ashes.

The major problem with coal fly ash is poor uniformity for certain properties in some sources. This is attributable to a number of things. Among them is the recent trend toward variability in the source of coal burned in power plants and variation in the operation of power plants. Operators of electric power plants alter operating conditions to increase the efficiency of generating electricity, with little concern about how this affects the quality of the ash. The vendors of the fly ash try to select the best product out of the waste stream, but sometimes things slip by, particularly if they are not covered by the C618 requirements.

---

[11] ASTM C350. Specification for Fly Ash for Use as an Admixture in Portland Cement Concrete (Withdrawn 1968)

Recent examples of problems attributable to fly ash variation include a strength compliance issue in airfield construction, concrete workability problems in a lock and dam construction, and a potential ASR issue in construction of windmill bases.

In the airfield case flexural strengths of the concrete had been running well above the acceptance limits, then over a period of about 6 weeks, strengths gradually declined to just barely meeting the required strength. Two lots did not meet requirements and were rejected and replaced at a cost of about $500,000.

The problem wasn't immediately detected due to the 28-day test period causing a delay in the contractor seeing the problem. It appeared that variation in fly ash fineness may have caused or at least contributed to this problem. Fineness of fly ash is an important property affecting strength gain in concrete.

The ash was much finer at the start of construction and was found to have become significantly coarser at the time of the very low strengths. There was insufficient data to be definitive on this, but it resembled some other case histories within Corps of Engineers construction. Also, effects of changing fineness on strength from proficiency sample testing supports this conclusion.

C618 contains provisions on fineness uniformity, but the structure of the requirement is such that it is difficult to implement without considerable confusion. As a result, variation in this property is often not monitored during construction.

The loss of workability in the lock and dam construction was traced to variability in the chemical composition of the Class C fly ash being used in rather large replacements for portland cement (40 – 50%). The result was that on some days the concrete would not hold slump for the few minutes required to transport it from the on-site batch plant to the location of the placement. After a long period of investigation and trials to try to solve this problem, the project switched to a Class F fly ash and the project was completed successfully. However, there was a claim for $15M for lost productivity and costs of switching to the Class F fly ash.

C618 contains no provisions on time of setting or lost workability caused by fly ash. This was a novel problem at the time, so understandably it would not be covered. However there has been no action on this, apparently because it isn't perceived to be a major problem for lower fly ash levels common to most concrete construction.

The case of the potential ASR problem in the windmill bases was traced to unusually high sodium content in the ash. Sodium salts are sometimes used in coal fired power generation as a processing addition to help control sulfur emissions. This has been a long-standing practice, but usually results in sodium contents low enough to be of no concern. In this case the high sodium content wasn't discovered until after the structures were built. Since the aggregate was considered to be ASR susceptible, these had to be removed and replaced. The cost was probably considerable.

C618 has no requirements on sodium content, probably since this had not been considered to be a potential issue. Most of the earlier work on ASR did not identify a major cause for concern of alkali content. The FHWA sponsored research described above did identify levels of alkali that should be avoided, but this had not yet made its way into the fly ash specification.

DISCUSSION

It is well recognized that standards for construction and construction materials are pivotal for insuring the anticipated service life of a structure. This essay has focused primarily on inadequacy of materials standards.

ASTM International is the primary standards development organization in the US. However the intention of this essay is not to criticize the ASTM. Rather ASTM is a long-standing (>100y) organization that has evolved a remarkable process for developing standards. The structure of the ASTM process insures due process for the interests of product users (Users), product producers (Producers), and the large category stakeholders that have no direct user or producer affiliation (General Interest). The General Interest group includes laboratory testing, equipment manufacturers, and independent consultants.

ASTM committees C1 and C9 cover concrete and concrete materials. However, ASTM, as a manger of standards development, makes no direct contribution to the technical contents of standards. It does set forth a required format and conceptual structure of standards. For example test methods are required to contain sections on scope, terminology, significance and use, procedure, precision and bias, etc.

The technical contents of ASTM standards are totally under the control of the voting members of the committees that manage the individual standards. Pivotal in this process is the balance between the Users and Producers. Historically, Users were the primarily interest group driving the aspects of standards that insure quality of construction and the long-term performance of a structure. Producers main interest has historically be to insure that the specifications were not unrealistically restrictive so as to interfere with commerce. The result is that standards tend to show a balance between these two objectives.

Two recent trends have changed this process some – both tied to money. Up until the last decade or so, participation by Users in concrete standards development was robust. Many of the current standards were motivated and their development paid for by this group. The standards that come out of this were remarkable but, as mentioned, there are some shortcomings that continue to cause us problems. The problems are often not within the interest of the Producer group, so can be neglected.

The User group is mainly derived from government agencies. Owners of commercial structures are another fraction, but typically not that active in standards development. In recent years, the participation in User group has seen a major decline, due largely to budgetary restrictions by US, state, and local governments. One large DoD organization rationalized this drawdown by proclaiming concrete technology to be a solved problem. Some large US governmental organizations are still involved and support R&D, but largely for development of new technologies, and not in solving issues in existing standards, which constitutes the bulk of what is used in construction.

The other major trend is the development of new procurement procedures for construction that restricts time and expenditures for preconstruction investigations of materials. This process favors sampling and testing that can be rapidly executed, sometimes overlooking the shortcomings that result.

Also a major part of the standards problem inhibiting efforts to improve standards is one of technical difficulty. Some properties are simply very difficult to measure with the precision necessary for the application. Some long-term durability phenomena are simply difficult to capture in a short-term laboratory test procedure and to determine meaningful acceptance limits on test results.

However, many of the shortcomings in specifications are derived largely from insufficient information on the relationship between the test results from a test method and field performance. This is a record management problem which could be significantly improved upon if owners of structures (Users) were more diligent in keeping design, QA/QC, and inspection and making these available for use in standards development.

The precision and bias shortcomings of test methods, which have been cited frequently in the examples discussed in this paper, present a very difficult problem. Determining the cause of this is not a simple matter of running interlaboratory round robins. Even these can be expensive, but they usually only confirm the poor precision. What is needed are robustness (C1067[12]) studies that evaluate the contribution to total variation from the individual steps, test conditions, and equipment details of a test method. It is very difficult to get funding for this kind of work.

In summary, materials standards do a reasonably good job of preventing materials related damage in concrete. However there is a chronic problem of instances when they do not. An improvement on the present condition largely depends on the User interest group in standards development to motivate solving these problems.

REFERENCES

1. Idorn, G.M., *Concrete Progress from Antiquity to the Third Millennium*, London, Thomas Telford, 1997.
2. Poole, Toy S., Weiss, Charles A., and Moore, Christopher, "Investigation of Damage to Concrete in Reregulation Dam, Carters Lake, GA," CMB 05-017, Vicksburg, Mississippi, US Army Corps of Engineers R&D Center (GM-C), 2005.

[12] ASTM C1067. Practice for Conducting a Ruggedness Evaluation or Screening Program for Test Methods for Construction Materials

3. COE, "Cooperative Freezing-and-Thawing Tests of Concrete Specimens," TM No. 6-395, Vicksburg, Mississippi, US Army Corps of Engineers, Waterways Experiment Station, 1954.
4. Tabb, B., Felice, R., Freeman, J.M., Frazier, R., Welchel, D., and Ley T., "A New Test Method to Measure the Freeze Thaw Durability of Fresh Concrete." Presentation (http://www.superairmeter.com/uploads/2/6/0/8/26084613/sam_website.pdf), 2014.
5. Rollings, R., "Alkali-Aggregate Reaction in Portland Cement Concrete (PCC) Airfield Pavements," ETL 06-2. Department of the Air Force, HQ Air Force Civil Engineering Support Agency, Tyndall AFB, Florida, 2006.
6. Thomas, M., Fournier, B., and Folliard, K., "Report on Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction," Report FHWA-HIF-009-001, Washington, DC., Federal Highway Administration, 2008.
7. Fournier, B, Ideker, J., Folliard, K., Thomas, M., Nkinambubanzi, P. and Chevrier, R., "Effect of Environmental Conditions on Expansion in Concrete Due to Alkali-Silica Reaction (ASR)," *Materials Characterization*, v. 60, 669-679, 2009.